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Introduction

The main achievements of the activity carried out under this grant have been an understanding of the mechanism of rain noise and of the role of bubble clouds in ambient noise generation at low frequencies.

The first problem has been investigated theoretically in conjunction with experiments carried out at the University of Mississippi by Prof. Larry Crum and co-workers. In addition to reaching an understanding of a puzzling "universality" of rain noise at low rainfall rates, we have for the first time produced entirely numerical rain noise spectra resembling the observed ones. As a consequence of the publicity reached by this work, the PI was asked to provide a review paper on the problem for the *Annual Reviews of Fluid Mechanics.*

Work on the second problem has been based on the initial observation of the PI (and, independently of Dr. W. Carey), originally formulated in a paper presented in 1985 at the Nashville meeting of the Acoustical Society of America, that bubble clouds could oscillate in collective modes at frequencies as low as a few tens of Hz, even though the constituent bubbles, in isolation, might have natural frequencies of tens of kHz or more. This hypothesis has now been widely confirmed both in the laboratory and in the field and constitutes the accepted answer to a puzzle that had remained unsolved since the original measurements of Knudsen during World War II.

The results of the work are documented in a series of papers listed below. The first page of each paper is also reproduced below. Additional information on the work carried out under this grant is provided in the annual summaries submitted to ONR and published in part in the series of annual volumes titled *Ocean Acoustics Program Summary.*

Student support

The following is a list of the students supported wholly or partially under the ONR grant:

1. ADRIANO M. LEZZI. Doctoral dissertation title: *Topics in Free-Surface Flows.* Johns Hopkins, 1990

2. NAN Q. LU. Doctoral dissertation title: *Bubble Clouds as Sources and Scatterers of Underwater Sound.* Johns Hopkins, 1990

3. RAMANI DURAISWAMI. Doctoral dissertation title: *Pressure Wave Propagation in Condensing Fogs.* Johns Hopkins, 1990

4. KAUSIK SARKAR. Doctoral dissertation title: *Effective Boundary Conditions for Rough Surfaces & Acoustics of Oceanic Bubbles.* Johns Hopkins, March 1994

5. MASAO WATANABE. Doctoral dissertation title: *Topics in Bubbly Liquid Flows and Cavitation.* Johns Hopkins, January 1995

6. HE YUAN. Doctoral dissertation title: *Dynamics of one and two bubbles in liquids.* Johns Hopkins, April 1996 (expected)

Papers

The following list does not include oral presentations at meetings of the Acoustical Society of America or at the American Physical Society Fluid Dynamics Division.

1. Oğuz, H.N. and Prosperetti, A. A generalization of the Impulse and Virial Theorems, *J. Fluid Mech.*, **218**, 143-162, 1990

2. Oğuz, H.N. and Prosperetti, A. Bubble entrapment by axisymmetric capillary waves. In *Engineering Science, Fluid Dynamics*, Yates, G. ed. World Scientific, 1990, pp. 191-202

3. Cannelli, G.B., D'Ottavi, E. and Prosperetti, A. Bubble activity induced by high-power marine sources. In *Proceedings of Oceans '90*, Washington, September 24-26 1990, IEEE, pp. 533-537.

4. Oğuz, H.N. and Prosperetti, A. Bubble Entrainment by the Impact of Drops on Liquid Surfaces, *Journal of Fluid Mechanics*, **219**, 143-179, 1990

5. Oğuz, H.N. and Prosperetti, A. Bubble Oscillations in the Vicinity of a Nearly Plane Free Surface, *The Journal of the Acoustical Society of America*, **87**, 2085-2092, 1990

6. Lu, N.Q., Prosperetti, A., and Yoon, S.W. Underwater noise emissions from bubble clouds, *IEEE Journal of Ocean Engineering*, **15**, 275-281, 1990.

7. Lezzi, A.M. and Prosperetti, A. The Stability of an Air Film in Liquid Flows, *Journal of Fluid Mechanics*, **226**, pp. 319-347, 1991

8. Oğuz, H.N. and Prosperetti, A. Numerical Calculation of the Underwater Noise of Rain, *J. Fluid Mech.*, **228**, 417-442, 1991.

9. Yoon, S.W., Crum, L.A., Prosperetti, A. and Lu, N.Q. An Investigation of the Collective Oscillations of a Bubble Cloud, *J. Acoust. Soc. Am.*, **89**, pp. 700-706, 1991.

10. Crum, L.A. and Prosperetti, A. The underwater sounds of precipitation, *Naval Research Reviews* **44**, 2-12, Two1992.

11. Oğuz, H.N. and Prosperetti, A. Drop impact and the underwater noise of rain. In *Natural Physical Sources of Underwater Sound*, Kerman, B.R. ed. Kluwer 1993, pp. 669-682.

12. Prosperetti, A., Lu, N.Q., and Kim, H.S. Active and Passive Acoustic Behavior of Bubble Clouds at the Ocean's Surface, *J. Acoust. Soc. Am.* **93**, 3117-3127, 1993

13. Prosperetti, A. and Oğuz, H.N. The impact of drops on liquid surfaces and the underwater noise of rain, *Ann. Rev. Fluid Mech.* **25**, 577-602, 1993.

14. Prosperetti, A. Bubble mechanics: luminescence, noise, and two-phase flow. In *Theoretical and Applied Mechanics 1992*, Bodner, S.R. et al. eds. Elsevier, 1993, pp. 355-369.

15. Nicholas, M., Roy, R.A., Crum, L.A., Oğuz, H.N. and Prosperetti, A. Sound Emissions by a Laboratory Bubble Cloud, *J. Acoust. Soc.* **95**, 3171-3182, 1994

16. Prosperetti, A. Bubble dynamics: Some things we did not know 10 years ago. In *Bubble Dynamics and Interface Phenomena*, Blake, J.R. et al. eds. Kluwer, 1994, pp. 3-16.

17. Oğuz, H.N. A theoretical study of low-frequency oceanic ambient noise, *J. Acoust. Soc. Am.* **95**, 1895-1912.

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A generalization of the impulse and virial theorems with an application to bubble oscillations

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In the first part of the paper it is shown that the impulse and virial theorems of inviscid incompressible fluid mechanics are special cases of a more general theorem from which an infinity of relations can be obtained. Depending on the problem, only a finite number of these relations may be independent. An application of these results is in the approximate study of the hydrodynamic interaction of bodies. As an example, in the second part of the paper, the case of two freely translating, nonlinearly pulsating bubbles is considered. It is found that in certain parameter ranges the force between the bubbles has a sign opposite to what would be expected on the basis of the linear theory of Bjerknes forces.

1. Introduction

Consider N closed material surfaces S_i in a finite or infinite region Ω occupied by a perfect fluid in irrotational motion. Then Blake & Cerone (1982) proved the following relation:

$$\frac{\mathrm{d}}{\mathrm{d}t}\sum_{i=1}^{N}\int_{S_i}\phi\boldsymbol{n}\,\mathrm{d}S_i = \int_B [\tfrac{1}{2}\boldsymbol{u}\cdot\boldsymbol{u}\boldsymbol{n}-(\boldsymbol{n}\cdot\boldsymbol{u})\,\boldsymbol{u}]\,\mathrm{d}S_B. \tag{1.1}$$

In this relation ϕ is the velocity potential, $\boldsymbol{u} = \nabla\phi$ is the velocity field, and $\boldsymbol{n}$ is the unit normal directed away from the fluid. By B we denote all the material surfaces bounding the region Ω other than $S_1, S_2, \ldots$ and the surface at infinity. In the absence of any boundary at a finite distance from the bodies, the right-hand side vanishes and this relation proves the time independence of the sum of integrals in the left-hand side, which is identified with the *impulse* of the fluid (or, more precisely, with the impulse divided by the density). Benjamin & Ellis (1966) and Blake and co-workers (Blake 1983, 1988; Blake & Cerone 1982; Blake & Gibson 1981, 1987; Blake, Taib & Doherty 1986) have given a number of examples of the application of this theorem in bubble dynamics.

Another integral theorem, only valid for an infinite region Ω, has been proven by Benjamin (1987) and, in a different way, by Longuet-Higgins (1989). In the previous notation this theorem may be written

$$\frac{\mathrm{d}}{\mathrm{d}t}\sum_{i=1}^{N}\rho\int_{S_i}-\phi\boldsymbol{x}\cdot\boldsymbol{n}\,\mathrm{d}S_i = -5E_{\mathrm{K}}+\sum_{i=1}^{N}\int_{S_i}(p-p_\infty)(\boldsymbol{x}\cdot\boldsymbol{n})\,\mathrm{d}S_i, \tag{1.2}$$

where E_{K} is the kinetic energy of the fluid, p is the pressure, ρ is the density and p_∞ the ambient pressure. The sum of integrals in the left-hand side is the *virial* of the motion.

In the present paper we shall generalize these results in two directions. First, we

Engineering Science, Fluid Dynamics (pp. 191 – 202)

BUBBLE ENTRAPMENT BY AXISYMMETRIC CAPILLARY WAVES

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ABSTRACT

Experiment and computation show that liquid drops impacting on a liquid surface can entrain air bubbles which play a very important role in the underwater noise of rain. To explore the physical mechanism responsible for this process, the dynamics of a large-amplitude, circular capillary wave is studied numerically. It is found that, as the wave propagates toward the axis of symmetry, nonlinear effects can lead to a steepening and overturning strikingly similar to those found in the impacting drop case. When it reaches the axis of symmetry, in suitable conditions, the wave is also able to entrap air bubbles.

1 Introduction

The fact that liquid drops falling on a liquid surface may entrain air bubbles has been known for some time.[1] However, it is only very recently that the detailed mechanics of this process has been elucidated in a beautiful set of experiments by Pumphrey and Crum.[2,3] Among other results, these authors have shown that bubble entrapment occurs in a small and well-defined region of the parameter space formed by the radius R of the impacting drop and its impact velocity V (Fig. 1). Furthermore, they have also shown that very little acoustic energy is radiated into the liquid by the impact itself, the most significant noise source being the volume pulsations of the entrained bubbles.

These observations have a very important bearing on the underwater noise produced by rain. The steep line on the left of Fig. 1 shows the terminal velocity

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BUBBLE ACTIVITY INDUCED BY HIGH-POWER MARINE SOURCES

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Abstract: This paper presents some preliminary results of a systematic study of the bubble phenomena associated with high-power sparker-based acoustic marine sources of a novel type. Data taken at sea and in a laboratory tank are presented and an attempt is made to interpret them in the light of a simple theoretical model.

Introduction

The function of any marine source of seismic energy is to generate a powerful acoustic wave in the water which is employed to explore sub-bottom sea structures.[1] As monopoles are the most efficient acoustic sources in a fluid, it is natural that bubble phenomena play a prominent role in the functioning of most of the sources developed to date. A drawback is however the fact that, in most cases, the bubbles produced by the sources give rise to more than one pressure pulse. The pressure waves associated to the bubble implosion and, in some cases, to the following oscillations, contaminate the signal and require sophisticated data-processing techniques for their removal.[2] The need to understand these bubble processes becomes more and more pressing with the contemporary trend toward the use of more powerful acoustic sources to penetrate deeper into the sub-bottom or to propagate underwater signals over large distances for long-range communication.

These considerations motivate a systematic study currently under way of the bubble activity induced by the high-power, paraboloidal, sparker-based marine source recently developed at the Istituto di Acustica "O.M. Corbino".[3,4] In comparison with traditional devices, this new source is characterized by a more controllable electronics and mechanics which makes it considerably more versatile. A set of experimental tests both in the laboratory and at sea has been initiated to study the dependence of its performance on different parameters and experimental conditions. In this paper we present some preliminary results of this study, in particular concerning the effect of the liquid temperature. On the basis of these experimental results, a simple theoretical model is developed to give a first interpretation of the observed phenomena.

Experimental tests

Some preliminary tests were carried out at sea off the coast of Fiumicino (Rome) in order to compare the behavior of the paraboloidal sparker-based source with that of a conventional sparkarray. The principle used to produce the pressure pulses in the two sources is the same, namely the discharge between pairs of electrodes in the liquid of a large electrical charge stored in a capacitor bank. However, in the paraboloidal source, the electric spark gap is positioned at the focus of a metallic paraboloidal reflector and the pulse generated is characterized by very high power in a wide range of low and middle frequencies (0.1 to 15 kHz) not usually available in standard commercial devices.

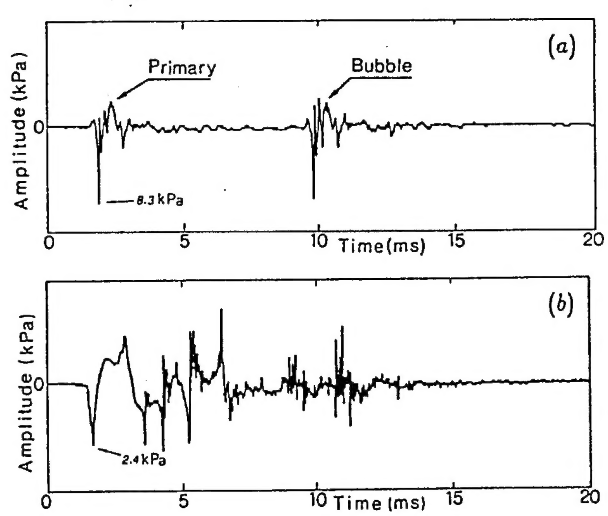

Figure 1: *Comparison between the acoustic signatures generated by the paraboloidal sparker-based source (a) and of a traditional sparkarray (b) in the same experimental conditions in sea water. The firing energy is 300 J.*

Figure 1 shows a comparison between the signatures of the two sources for a firing energy of 300 J. [Note that, in this as in the following figures, the polarity is reversed so that a compression appears as a decrease of the amplitude.

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Bubble entrainment by the impact of drops on liquid surfaces

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(Received 19 May 1989 and in revised form 2 March 1990)

The impact of a drop on the plane surface of the same liquid is studied numerically. The accuracy of the calculation is substantiated by its good agreement with available experimental data. An attempt is made to explain the recent observation that, in a restricted range of drop radii and impact velocities, small air bubbles remain entrained in the liquid. The implications of this process for the underwater sound due to rain are considered. The numerical approach consists of a new formulation of the boundary-element method which is explained in detail. Techniques to stabilize the calculation in the presence of strong surface-tension effects are also described.

1. Introduction

The fact that a water drop impinging on a water surface may lead to the entrapment of an air bubble at the bottom of the crater that it produces has been known for some time (Franz 1959). However, the intricate features of this phenomenon have only recently been clarified by Pumphrey & Crum (1988; see also Pumphrey, Crum & Bjørnø 1989) in the course of an experimental study of the mechanism of rain noise. While their results will be summarized in some detail in the next section, we mention here that they discovered that, far from being a random event as suggested by Franz, bubbles remain entrapped under very well-defined conditions and lead to a very substantial noise emission in the water. The significant consequences of this finding for the generation of underwater noise by rain have been addressed elsewhere (Prosperetti, Pumphrey & Crum 1989) and are summarized in the last section of this paper. Here we wish to study theoretically the fluid dynamics of crater formation and bubble entrapment and develop a qualitative understanding of the physics involved in these processes. Our main tool is numerical, and the dominant effect of surface tension on the process has required the development of a stable boundary-integral method which is of interest in itself and is described in detail.

The study of drop impact on liquid surfaces has a long history that goes back to the end of the last century when Worthington (1894) studied the process by means of single-flash photography. Quite famous are also the high-speed photographs of Edgerton (Edgerton & Killian 1939). These researchers, as well as others such as Engel (1967) and Macklin & Metaxas (1976), studied, however, impacts at relatively high speeds and therefore missed many interesting aspects of the process that were recently identified by Pumphrey and Crum. One of the early applications of the MAC code also dealt with drop impact on a liquid layer (Harlow & Shannon 1967*a*, *b*), but again, as pointed out by Carroll & Mesler (1981*a*, *b*), many subtleties were missed because of the incomplete treatment of surface-tension phenomena. The same

Bubble oscillations in the vicinity of a nearly plane free surface

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The linear oscillation frequency of a bubble in the vicinity of a distorted plane free surface is calculated by a perturbation method. The approximate expression found is compared with numerical results valid for surface deformations of arbitrary magnitude. It is found that the approximate analytical result is quite good, provided that the deformation is small compared with the depth of immersion of the bubble. It is also shown that, unless the deformation of the free surface extends to distances at least of the order of an acoustic wavelength, the "image" bubble has the same source strength of the real bubble so that a dipolar acoustic emission can be expected in spite of the deformation of the surface.

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INTRODUCTION

Recent work shows that a substantial contribution to oceanic ambient noise is caused by the free oscillations of air bubbles entrained by breaking waves, by impacting rain drops or sprays, or possibly by capillary waves of limiting form.[1–7] In all these cases, at the instant when the surface closes, the resulting bubble is not, in general, in equilibrium. The excess initial energy is dissipated in the course of shape and volume oscillations that give rise to the acoustic emission.

Although a great deal is known about the oscillations of bubbles in unbounded liquids (see, e.g., Refs. 8–13), it is not obvious that this information is applicable to the circumstances described above because, during the acoustic emission, the bubble is near the ocean surface, and this surface is not plane.

A typical example is shown in Fig. 1 (with the permission of H. C. Pumphrey and L. A. Crum), which is a frame from a high-speed movie film of a water drop falling on an undisturbed water surface. The left side of the frame shows a bubble that has just detached from the bottom of the crater created by the impact. The right side of the frame shows the oscilloscope trace produced by a hydrophone driven by the sound pulse emitted by the bubble. The frequency of the damped sinusoid measured from this photograph is approximately 7 kHz, and the bubble diameter, measured from a later frame in which the bubble is in equilibrium, is 0.95 mm. It is most remarkable that, in spite of the proximity of the highly distorted free surface, this frequency is in almost perfect agreement with the natural frequency of a bubble of the same radius in an unbounded fluid, which equals 6.78 kHz.

In the present paper, we try to find a theoretical justification for this fact on the basis of a perturbative solution of the problem. The approximation results are checked against numerical ones, and their domain of validity is established. In the last section, we offer some comments on the expected acoustic radiation from the bubble under these conditions.

The basis of our approximation consists in the fact that, in many situations of interest, the distortion of the free surface has a scale larger than the bubble radius and the distance of the bubble from the free surface is not small. The first circumstance arises because, in general, the events that render the free surface multiply connected are so energetic as to produce disturbances on a much larger scale than the bubble. Second, in the neighborhood of the point from which the bubble detaches, the curvature is very large. As soon as the bubble is formed, therefore, under the action of surface tension, this local, high-curvature deformation disappears very

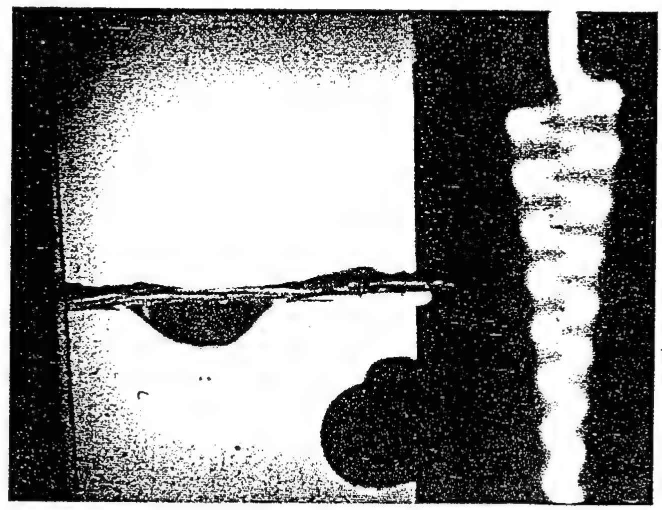

FIG. 1. A frame from a high-speed cinematographic sequence showing the entrapment of an air bubble when a drop hits a liquid surface (courtesy of H. C. Pumphrey and L. A. Crum). The left half of the frame shows the physical event. One can see the free surface indented by the crater caused by the impact and, directly under it, the bubble that has just detached. The shadow in the lower right is a hydrophone that drives an oscilloscope the trace of which is shown, vertically, in the right half of the frame. The right half of the picture shows therefore, in a sense, the "soundtrack" of the left half. The damped sinusoid of the oscilloscope trace is the acoustic signal produced by the volume oscillations of the bubble. A study of the angular distribution of the signal reveals the expected dipole pattern. See Refs. 3–5 for further details.

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Underwater Noise Emissions From Bubble Clouds

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(Invited Paper)

Abstract—By means of an effective equation model for the propagation of pressure waves in a bubbly liquid, the normal modes of oscillation of regions of bubbly liquid in an otherwise pure liquid are calculated for some simple geometries. It is shown that the frequencies of oscillation of such bubble clouds can be very much lower than those of the constituent bubbles in isolation and fall well within the range where substantial wind-dependent noise is observed in the ocean. A comparison with some experimental data very strongly supports the theoretical results.

I. Introduction

IN THE OCEAN, bubble clouds are incessantly formed in the upper layers by the breaking of waves and are transported to depths of tens of meters by Langmuir circulation, turbulence, and other mechanisms [1], [2]. One might expect these bubbles to contribute substantially to the underwater ambient noise, since wave breaking is a catastrophic event that will certainly impart them an appreciable initial energy [3]–[7]. That a substantial part of this acoustic emission could be at frequencies well below a few kilohertz, however, may at first sight be surprising. Indeed, from the approximate relation

$$\omega_0^2 \simeq \frac{3P_0}{a^2\rho} \tag{1}$$

relating the bubble radius a to its natural frequency $\nu_0 = \omega_0/2\pi$, one finds, for example, $\nu_0 \simeq 2.8$ kHz for a bubble having the radius of 1 mm in water (density $\rho \simeq 1$ g/cm^3) at normal ambient pressure ($P_0 \simeq 1$ atm). However, bubbles in a cloud are in effect coupled oscillators, and one can therefore expect the existence of *normal modes* of the cloud itself at a substantially lower frequency than that of the individual constituent bubbles. An alternative argument leading to the same conclusion may be based on the observation that the speed of sound in a bubbly mixture can be an order of magnitude smaller than in the pure liquid, even at gas-volume fractions less than 1%. Therefore, to a first approximation, a region of bubbly liquid can be considered as enclosed by a rigid boundary and will then possess normal modes. However, the fact that the boundary is not really rigid has the consequence that the acoustic energy "trapped" in the bubbly region will leak out into the pure liquid.

The frequencies ω_k of these normal modes are readily estimated as follows [7]. Let the cloud have linear dimensions of order L. Then, from the analogy with similar systems [8], one expects eigenfrequencies of the order of $\omega_k \simeq kc_m/2L$, $k = 1, 2, \cdots$, where c_m is the effective speed of sound in the bubbly mixture given approximately by the well-known expression [9]–[11]:

$$c_m^2 \simeq \frac{P_0}{\rho\beta} \tag{2}$$

where β is the gas-volume fraction. If the constituent bubbles have a radius of order a, the gas-volume fraction may be estimated by $\beta \sim (a^3/L^3)N$, where N is the number of bubbles in the cloud. In this way we find:

$$\frac{\omega_k}{\omega_0} \sim \frac{k}{\beta^{1/6}N^{1/3}}. \tag{3}$$

The volume fraction here is raised to such a low power that the result is nearly independent of this variable. Hence all the frequencies, and in particular the lowest one corresponding to $k = 1$, are predicted to decrease essentially as the cube root of the bubble number. For $N \sim 1000$, the frequency reduction with respect to the single-bubble case would be of one order of magnitude [7].

The preceding estimate can be put on a firmer ground by means of a model of a bubbly liquid which is adequate up to gas-volume fractions of a few percent. The model, which regards the gas–liquid mixture as a continuum governed by effective equations, is essentially due to Foldy [12], and has been rederived by many others, in particular in [13]. Its predictions have been compared with experiment, most recently in [14], and a very good agreement was found. For completeness we briefly present the linearized version of this model in the next section. A series of papers containing detailed applications of it to the generation and scattering of sound by bubble clouds of different shape and in a number of situations is being prepared. The present study is a survey of the results on the generation of noise contained in these papers.

II. Mathematical Formulation

The averaged continuity and momentum equations applicable to a bubbly liquid at small gas-volume fraction may be

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The stability of an air film in a liquid flow

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A number of processes in which air is entrained in a flow appear to involve the formation of a thin air film between a relatively fast liquid stream and a region of slow recirculation. Eventually, the film breaks into bubbles. This study addresses a possible mechanism causing this process. The linear stability of a vertical film of a viscous gas bounded by liquid in uniform motion on one side, and by liquid at rest on the other side, is studied. Instabilities are found that, depending on the parameter values of the undisturbed flow, are controlled by two basic mechanisms. One is due to the velocity jump across the film and can be related to the usual Kelvin–Helmholtz instability. The second one is controlled by the viscosity jump across the air–liquid interfaces. The relation between the remainder of the discrete spectrum and the spectrum of other parallel shear flows bounded by solid or free surfaces is also discussed.

1. Introduction

The entrainment of air in a flow is an important process very frequently encountered. The ecological balance of water bodies, from small lakes to entire oceans, is critically dependent on the amount of dissolved oxygen. Aeration is a standard technique of water treatment. Furthermore, the formation and detachment of bubbles is an inherently noisy process to which much of the oceanic ambient noise over a large frequency range from hundreds of Hz to many tens of kHz can be ascribed. In spite of this widespread occurrence, not much seems to be known about the basic mechanisms by which entrainment takes place. In a paper devoted to air entrainment in a wave breaking in the spilling mode, Longuet-Higgins & Turner (1974) mention the 'over-running of air by the advancing front' of water and the 'self-aeration' of thin, highly turbulent flows which develops when the turbulent boundary layer on the bottom reaches the surface. While certainly correct and adequate for the purposes of their study, these statements are rather vague as to the precise nature of the process. A literature search has not produced much more detailed information than this. In the present paper we wish to investigate theoretically a possible mechanism by which air can be entrained in flows. Although not the only one, this mechanism appears to be of sufficiently widespread occurrence to warrant its investigation.

A consideration of several examples of entraining flows suggests that a possible mechanism involves the development and instability of a thin air film at the boundary between two liquid currents. The clearest example of this process is offered by a jet falling into a liquid pool. In a high-viscosity liquid an air film surrounding the jet can be clearly discerned for several diameters below the free surface (Lin & Donnelly 1966). The film develops a wavy structure, the amplitude of which

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Numerical calculation of the underwater noise of rain

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(Received 15 March 1990 and in revised form 31 October 1990)

When raindrops with a diameter of the order of 1 mm hit a plane water surface they entrain air bubbles that radiate noise in the course of volume oscillations. The paper presents a model of the underwater noise of rain produced by this process. The depth of submergence, radius, and initial energy of the entrained bubbles are obtained numerically for a number of drop sizes. The bubbles are assumed to radiate as dipoles, and the total underwater noise is calculated by integrating over the size of the entraining rain drops. The results are compared both with laboratory experiments of single-drop impacts and field data of rain noise. It is found that the model gives somewhat larger bubbles than are observed experimentally. As a consequence, the characteristic spectral peak of rain is predicted to occur at a somewhat lower frequency than found in experiment. However the level of the peak is in reasonable agreement with data. The amount of noise due to the process of drop impact itself is also estimated and found to be several orders of magnitude lower than the data. Therefore, in spite of some deficiencies of the model and of the computational results, the proposed mechanism for the underwater noise of rain is strongly supported by this study.

1. Introduction

The underwater noise produced by rain has recently been measured by a number of groups and in different conditions (Scrimger 1985; Scrimger *et al.* 1987; Scrimger, Evans & Yee 1989; Nystuen 1986; Nystuen & Farmer 1989; Pumphrey, Crum & Bjørnø 1989). A striking finding common to all these studies is the presence of a very prominent and well-defined spectral peak at a frequency of approximately 14 kHz. Quite unexpectedly, the position and general shape of this peak are found to be independent of the rainfall rate, and even of the size distribution of the rain drops. A striking example, from Scrimger *et al.* (1987), is reproduced in figure 1. Figure 1 (*a*) shows the measured raindrop size distributions for two rain events, the underwater noise of which is shown in figure 1 (*b*). It can be seen that the size distributions look very different, while the measured spectra are strikingly alike. Some other examples can be found in Scrimger *et al.* (1987).

In a recent study (Prosperetti, Pumphrey & Crum 1989) we have proposed an explanation for these findings based on the fluid mechanics of the impact of drops on liquid surfaces. The starting point is work by Pumphrey & Crum (1988), Pumphrey *et al.* (1989), Pumphrey & Crum (1990) and Pumphrey & Elmore (1990) which presents conclusive evidence that most of the noise produced by impacting droplets at normal incidence is not actually produced by the impact itself, but by small air bubbles entrained by the impacting drop. A remarkable feature of this process is

An investigation of the collective oscillations of a bubble cloud

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It is well known that ocean ambient noise levels in the frequency range from a few hundred hertz to several tens of kilohertz are well correlated with wind speed. A physical mechanism that could account for some of this sound generation is the production of bubble clouds by breaking waves. A simple laboratory study of the sound generated by a column of bubbles is reported here. From measurements of the various characteristics of this column, good evidence is obtained that the bubbles within the column are vibrating in a collective mode of oscillation. Based upon an assumption of collective oscillations, analytical calculations of the predicted frequency of vibration of this column as well as the dependence of this frequency on such parameters as bubble population and column geometry agree closely with the measured values. These results give evidence that the bubble plumes generated by breaking waves can be a strong source of relatively low frequency (< 1 kHz) ambient noise.

PACS numbers: 43.30.Nb

INTRODUCTION

The literature contains substantial evidence that oceanic ambient noise is wind-dependent down at least to frequencies of a few hundred hertz.[1-3] The nature of the source of these low-frequency acoustic emissions is, however, still obscure. In view of this seeming correlation with breaking waves, it was suggested independently by Carey[4-6] and Prosperetti[7-9] that the collective oscillations of *bubble clouds* could explain these emissions. It is the purpose of the present paper to present an experimental confirmation of this possibility, and to show that analytical predictions agree closely with the measurements.

It is well known that bubbles abound in the first several meters under the ocean surface. Their origins are varied (impact of splashes, sprays, rain drops, biological activity, capillary waves of limiting form, and other mechanisms), but probably the most significant source of these bubbles is the breaking of surface waves.[10-12] The precise nature of the mechanism of air entrainment in a breaking wave is still poorly understood,[13] but it is plausible that at the moment at which the liquid surface closes on itself to entrap bubbles, its local velocity is nonzero. The bubble created in this way has therefore some initial kinetic energy and, unless it is spherical and with a balanced initial pressure, some initial potential energy as well. Since a bubble may roughly be regarded as a mechanical oscillator, one expects this initial energy to give rise to volume pulsations with associated acoustic emissions. The reason why such a simple picture is unacceptable as an explanation for the observed low-frequency noise is that the natural angular frequency ω_0 of a bubble of radius a is given approximately by

$$\omega_0 = (1/a)(3\gamma p_0/\rho)^{1/2},$$

where p_0 is the ambient pressure, ρ is the water density, and γ is the ratio of specific heats. With $p_0 = 10^5$ Pa, $\rho = 10^3$ kg/m^3, $\gamma = 1.4$, this relation would require a radius of about 7 mm for a frequency $f \doteq \omega_0/2\pi = 500$ Hz, and it is by no means clear—and actually rather unlikely—that such large bubbles are created in significant numbers.

The collective oscillation hypothesis circumvents this problem by appealing to the well-known fact that a system of coupled oscillators (such as the bubbles in the cloud, for which the coupling is provided by mutual hydrodynamic and acoustic interaction) possesses normal modes the frequencies of which can be substantially lower than the natural frequencies of the individual oscillators. An intuitive argument leading to the same conclusion is as follows. It is well known that a mixture of air bubbles and liquid has a sound speed much lower than that of the pure liquid even at gas volume fractions as low as 1%. As a rough approximation, one can therefore consider a bubble cloud as an acoustic medium surrounded by a rigid enclosure, a system which is capable of normal modes of oscillation depending on its linear dimensions. Since the surrounding liquid is not, however, a rigid enclosure, the energy trapped in the cloud will "leak out" and be detectable as acoustic waves away from the bubble cloud. A very simple argument shows that the ratio of the minimum cloud eigenfrequency ω_m to the natural frequency ω_0 of the constituent bubbles (assumed to be equal) is of the order of[14]

$$\omega_m/\omega_0 \sim 1/\beta^{1/6} N_b^{1/3},$$

where β is the gas volume or void fraction in the cloud and N_b is the total number of bubbles. For example, a region with linear dimensions of the order of 10 cm and a void fraction of 1% could contain enough 1 mm radius bubbles to cause a frequency reduction of one order of magnitude.

The theoretical literature on bubble cloud collective-oscillation phenomena has seen several contributions in the last few years.[4-9,14-17] However, so far, no direct experimen-

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The Underwater Sounds of Precipitation

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Abstract

The Office of Naval Research has supported a research program at our respective institutions for the past few years in the general area of bubble-related ambient noise in the ocean. In the course of our study of this topic, we came to discover some interesting things about the underwater sounds produced by the impact of rain, hail and snow on the surface of the sea. This paper describes the physical processes that produce these acoustic emissions and shows that a major portion of precipitation noise is caused by the injection of gas bubbles into the liquid by the impact of rain drops, hail stones and snow flakes.

Introduction

The distinctive sound of a raindrop striking a puddle of water is familiar to us all. It is one of those unique sounds in nature that is immediately recognizable. The sound of a pebble tossed into a quiet pond has a similar uniqueness and, to most of us, even evokes a sense of tranquillity. The soft, acoustic environment of falling snow is the very essence of stillness. We have examined these forms of precipitation and have found that the noise produced when they impact a water surface has at its origin an oscillating gas bubble. The study of the underwater sounds produced by precipitation is part of our general study of bubble-related ambient noise in the ocean, which has been supported by the Ocean Acoustics Program of the Ocean Sciences Directorate, Office of Naval Research.

Historical Background

Precipitation plays an important role in the climate of a particular region and, more generally, in our total global environment. Its occurrence has relevance to latent heat release, upward mass flux, and the spatial organization of convection. Thus, knowledge of the rate of rainfall and its geographical distribution is of major interest.

Due to rain's spatial and temporal discontinuity, accurate measurements are difficult even over land because rain gauges at discrete sampling sites can give misleading values. Radar can provide a more complete coverage, but its general use is restricted to the developed countries. Rainfall measurements over the ocean where – according to estimates[1] – 80% of the earth's precipitation occurs, are yet more difficult to obtain. Typically, the few weather stations located on the ocean are on islands, a circumstance that leads to an inadequate sampling of the global distribution. Shipboard measurements suffer problems such as contamination by sea spray, platform instabilities, and spatially-biased sampling.

Satellite-based, remote sensing of the earth's environment probably provides the highest promise for adequate global rainfall monitoring. Yet, such measurements are time-consuming, costly, and suffer the important limitation of "ground-truth," i.e., adequate land- or sea-based calibration.

It is against this background that Walter Munk's idea of using the underwater noise produced by rain to monitor rainfall rates remotely over the ocean can be appreciated. His suggestion was taken up by Nystuen, Scrimger, and others[2-4] in the early eighties with very unexpected and intriguing results.

DROP IMPACT AND THE UNDERWATER NOISE OF RAIN

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ABSTRACT. Experiment and theory give very strong indications that most of the underwater noise of rain in the region between 8-10 kHz and 20-25 kHz is due to the oscillations of bubbles entrained by the rain drops impacting on the ocean's surface. We present a theoretical calculation of the noise spectrum of this process and examine the effects of viscosity and other factors on this result. It is found that neglect of dissipative effects can lead to bubble sizes greater than observed experimentally.

1 Introduction

Recent experimental work by Crum and co-workers has given conclusive proof that air bubbles entrained when a liquid drop hits a plane surface are acoustic sources of far greater magnitude than the impact itself [1-3]. This work also shows that, for drops impacting at their terminal velocity, only a restricted range of drop radii, between 0.41 and 0.53 mm approximately, will result in the entrainment of a bubble. These results suggest a possible mechanism for the peculiar frequency dependence of the underwater noise of rain that seems always to exhibit a spectral peak near 14 kHz [4, 5]. The argument is that the acoustic signal depends only on such a narrow size range of drop sizes that the drop distributions of different rain events would be very similar in this range, the differences being mostly confined to the total drop count. Hence the acoustic spectra of different rain events would be very similar in relative spectral composition, the main difference being the absolute "loudness" of the noise [6].

In a recent study [7] we have attempted to reproduce purely theoretically, without recourse to experimental information, the underwater noise of rain. We calculate the size and the initial energy of the bubbles entrained by rain drops, and assume that they execute damped harmonic oscillations. The noise spectra generated in this way bear a striking resemblance to those of naturally occurring rain noise, except that the peak frequency occurs at a frequency of 8-9 kHz rather than 14 kHz. In the following section we present a summary of this earlier work, and then devote the rest of the paper to analysing some of the possible causes of this discrepancy.

B. R. Kerman (ed.), Natural Physical Sources of Underwater Sound, 669–682.

Active and passive acoustic behavior of bubble clouds at the ocean's surface

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The emission and scattering of sound from bubble clouds is studied theoretically. It is shown that clouds having a size and air content similar to what might be expected as a consequence of the breaking of ocean waves can oscillate at frequencies as low as 100 Hz and below. Thus cloud oscillations may furnish an explanation of the substantial amount of low-frequency wind-dependent oceanic ambient noise observed experimentally. Detailed results for the backscattering from bubble clouds—particularly at low grazing angles—are also presented and shown to be largely compatible with oceanic data. Although the cloud model used here is idealized (a uniform hemispherical cloud under a plane water free-surface), it is shown that the results are relatively robust in terms of bubble size, distribution, and total air content. A similar insensitivity to cloud shape is found in a companion paper [Sarkar and Prosperetti, J. Acoust. Soc. Am. 93, 3128–3138 (1993)].

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INTRODUCTION

Recent research has brought to the fore the importance of bubble clouds at the ocean's surface for the propagation and generation of underwater sound (Carey and Bradley, 1985; Carey and Browning, 1988; Prosperetti, 1985, 1988a,b; Lu *et al.*, 1990; Yoon *et al.*, 1991; Lu and Prosperetti, 1993). On the one hand, it has been realized that the clouds can oscillate in collective modes and give rise to acoustic emissions as low as a few tens of Hz irrespective of the size of the constituent bubbles. It is possible that in this fact an explanation may be found of the low-frequency component of wind-dependent oceanic ambient noise that has long puzzled investigators (Wenz, 1962; Kerman, 1984; Carey and Wagstaff, 1986; Kewley *et al.*, 1990). Secondly, several analyses have shown that the backscattering produced by bubble clouds can be quite substantial and preliminary estimates indicate that these entities may be responsible for the unexpectedly high backscattering strengths found experimentally.

The presence of bubbles in substantial numbers in the uppermost several meters of the ocean surface is so well known that a few references will be sufficient in this respect (Monahan, 1971; Thorpe, 1982; Farmer and Vagle, 1989). One may distinguish between the regions of "fresh" bubbles, newly formed by breaking waves, and the "old" bubbles, that are stabilized by still unclear mechanisms and survive long after their formation. Typically, "fresh" bubbles are relatively highly concentrated in clouds very close to the surface, while "old" bubbles are much less dense and are transported downward by turbulence and Langmuir circulation. We refer to these latter agglomeration as bubble "plumes" reserving the term "cloud" for the former.

In this paper we consider both the active and passive facets of the acoustic behavior of bubble clouds. Our model is geometrically simple and consists of hemispherical clouds at the surface of a plane ocean. However, we use a relatively complete model for the bubbly region that goes beyond previous calculations and we solve exactly—rather than in an approximate fashion—the emission and scattering problems. In our basic model the bubble cloud has a uniform spatial distribution of gas and bubble radii. Later, we consider generalizations of this model and try to derive conclusions of more general validity. The dependence of the results on the cloud shape is clearly also important, and is addressed in a separate publication (Sarkar and Prosperetti, 1993a).

Crowther (1980), McDaniel and Gorman (1982, 1983), and McDaniel (1987) have applied incoherent scattering methods to the calculation of backscattering from bubble layers. More recently, McDonald (1991) and Henyey (1991) have treated the backscattering from bubble plumes by the Born approximation. The methods used by these authors are not suitable for the denser bubble assemblies studied in this paper. A detailed comparison of these approaches can be found in Sarkar and Prosperetti (1993a, 1993b).

Perhaps the major piece of information missing for a quantitative description of bubble clouds is the gas concentration by volume, also called void fraction in the multiphase flow literature. Some estimates of this quantity during the active breaking process are as high as 30% (Longuet-Higgins and Turner, 1974; Melville *et al.*, 1992), but this situation of extremely large void fraction must be

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THE IMPACT OF DROPS ON LIQUID SURFACES AND THE UNDERWATER NOISE OF RAIN

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KEY WORDS: bubble entrainment, bubble noise, liquid impact, splash

INTRODUCTION

> There will be but few of my readers who have not, in some heavy shower of rain, beguiled the tedium of enforced waiting by watching, perhaps half-unconsciously, the thousand little crystal fountains that start from the surface of pool or river; noting now and then a surrounding coronet of lesser jets, or here and there a bubble that floats for a moment and then vanishes.
>
> It is to this apparently insignificant transaction, which always has been and always will be so familiar, and to others of a like nature, that I desire to call the attention of those who are interested in natural phenomena; hoping to share with them some of the delight that I have myself felt, in contemplating the exquisite forms that the camera has revealed, and in watching the progress of a multitude of events, compressed indeed within the limits of a few hundredths of a second, but none the less orderly and inevitable, and of which the sequence is in part easy to anticipate and understand, while in part it taxes the highest mathematical powers to elucidate.

Thus begins the book *A Study of Splashes* (1908) in which A. M. Worthington (1852–1916) presents "in a form acceptable to the general reader the outcome of an inquiry conducted by the aid of instantaneous photography, which was begun about fourteen years ago." Worthington's fascination with these phenomena actually went all the way back to 1875 (he was then 23 years old), when H. F. Newall, a student at the famous Rugby boys' public school, gave a report at the Rugby Natural History

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Bubble mechanics: luminescence, noise, and two-phase flow

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Abstract

A descriptive treatment of light emission from pulsating bubbles (sonoluminescence), sound generation by rain falling on water and breaking waves, and the propagation of shock waves in bubbly liquids is presented. The first section contains a brief survey of some occurrences of bubbles in literature and in the figurative arts. Considerations on the etymology of the word are presented in the appendix.

1. INTRODUCTION

Πομφόλυξ ο άνθροπος – Man is a bubble – is an ancient Greek proverb that enjoyed a singular favor in the western culture as an expression of the caducity and impermanence of human life. It is used by a number of Latin and Greek authors such as Varro who, apologizing in the Preface to his *De Re Rustica* (36 b.c.) that the work is not as polished as he would like, says that nevertheless, being 80 years old, he should go ahead with its publication since, "ut dicitur, si est homo bulla, eo magis senex" ("if, as they say, man is a bubble, all the more so is an old man"). Petronius (1st century a.d.), in a mocking passage of the *Satyricon* in which he compares man to inflated walking bags and flies, also says "nos non pluris sumus quam bullis" ("we are no more than bubbles," 42, 4). Lucian (117-180) elaborates: "I've thought of a simile to describe human life as a whole ... You know the bubbles that rise to the surface below a waterfall – those little pockets of air that combine to produce foam? ... Well, that's what human beings are like. They're more or less inflated pockets of air ... but sooner or later they're all bound to go pop" (*Charon* 19).

The advent of Christianity, with its message of hope and salvation, rendered the idea less relevant and probably the only pre-Renaissance textual reference to it is in the *Lexicon* by the 10th-11th century Byzantine scholar Suida ("as a bubble immediately disappears when it is broken, so does the memory of the splendid and powerful upon their death").

However, in the northern post-reformation cultural climate of the 16th and 17th century, the metaphor regained its appeal. Most succint – and first – is Erasmus: "Homo bulla" [man (is a) bubble, *Adagia*, 1508, n. 1990]. Taverner, in his *Proverbs or adagies ... gathered out of the Chiliades of Erasmus* (1539) echoes the concept, and so does sir Thomas Elyot (1545), Golding ("When man seemeth to bee at his best, he is al-

Sound emissions by a laboratory bubble cloud

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This paper presents the results obtained from a detailed study of the sound field within and around a cylindrical column of bubbles generated at the center of an experimental water tank. The bubbles were produced by forcing air through a circular array of hypodermic needles. As they separated from the needles the "birthing wails" produced were found to excite the column into normal modes of oscillation whose spatial pressure-amplitude distribution could be tracked in the vertical and horizontal directions. The frequencies of vibration were predicted from theoretical calculations based on a collective oscillation model and showed close agreement with the experimentally measured values. On the basis of a model of the column excitation, absolute sound levels were analytically calculated with results again in agreement with the measured values. These findings provide considerable new evidence to support the notion that bubble plumes can be a major source of underwater sound around frequencies of a few hundred hertz.

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INTRODUCTION

Wave breaking is the most significant air-entrainment process occurring at the surface of the ocean and gives rise to a large number of bubble clouds (Thorpe, 1982, 1986; Thorpe and Hall, 1983; Monahan and Mac Niocaill, 1986; Monahan and Lu, 1990). It is known that the number and intensity of breaking waves are strongly dependent on the wind speed above the ocean surface (see, e.g., Toba and Koga, 1986; Phillips, 1988; Wu, 1988), and it has also been shown that a correlation exists between wind speed and the intensity of low-frequency (below 1 kHz) ambient sound in the ocean (Wenz, 1962; Piggott, 1964; Perrone, 1969; Kerman, 1984; Kuperman and Ferla, 1985; Wille and Geyer, 1985; Carey and Wagstaff, 1986; Kennedy and Goodnow, 1990; Kewley *et al.*, 1990; Kennedy, 1992). These circumstances have led to the consideration of processes by which breaking waves may produce such low-frequency noise (Wilson, 1980; Kerman, 1984). Carey and co-workers (Carey and Bradley, 1985; Carey and Browning, 1988) and, independently, Prosperetti (1985, 1988a, 1988b) have suggested that collective oscillations of the bubble clouds produced by breaking waves could be responsible for the low-frequency emissions. The argument was essentially that, since the bubbles in the cloud constitute a collection of coupled oscillators, one would expect the existence of normal modes of oscillation of the cloud itself at frequencies far lower than the frequency of oscillation of the individual bubbles. This idea has been explored in, and supported by, a number of subsequent publications (Lu *et al.*, 1990; Yoon *et al.*, 1991; Carey *et al.*, 1993; Prosperetti *et al.*, 1993; Koller and Shankar, 1993; Oğuz, 1994).

In view of the difficulty in gathering oceanic field data on the role of bubble clouds in low-frequency sound generation, the conclusions mentioned above rest mainly on theoretical analyses only partially verified in laboratory experiments. It is therefore important to validate further the theoretical models used so as to gain confidence in their predictions. Initial experiments (Yoon *et al.*, 1991) have shown that bubble clouds are capable of collective oscillations at frequencies far below those of the individual constituent bubbles in excellent agreement with theory. In this paper that work is extended in two significant ways. In the first place, the use of a much more extensive data set renders the measurement of the higher mode frequencies possible with a very good match with theory. Second, the model is extended to the prediction of the *absolute acoustic levels*, again in good agreement with data. This is a very nontrivial point as it presupposes a quantitative understanding of the mechanism by which the bubble cloud is excited. Our conclusion is that the energy imparted to the individual bubbles upon their formation coupled with the spectral width of single-bubble free oscillations accounts for the level of acoustic radiation observed in the experiment. In a separate study (Oğuz, 1994), it is shown that, on the same basis, good predictions of low-frequency oceanic ambient noise can be found. These successful estimates of levels are a stringent test of the theory as it is well known that, in general, it is much easier to match frequencies than levels.

I. EXPERIMENTAL PROCEDURE

The experimental arrangement used in this work is very similar to the one described in Yoon *et al.* (1991) and

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Bubble dynamics:

Some things we did not know 10 years ago

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Abstract. This paper contains a brief review of the author's work on several problem related to bubble dynamics. A "state-of-the-art" model for spherical dynamics is formulated first. On the basis of this model several features of the thermo-fluid mechanical behavior of gas bubbles are then discussed and applications to sonochemistry and mass transfer described. The paper ends with a brief discussion of pressure wave propagation in bubbly liquid and the role played by bubbles in the generation of oceanic ambient noise.

Key words: Bubbles, Bubbly liquids, Acoustic cavitation, Oceanic noise

1 Introduction

The period since the 1981 IUTAM Symposium on Mechanics and Physics of Bubbles in Liquids [1] held at the California Institute of Technology in Pasadena has seen a tremendous growth in bubble research, both fundamental and applied. I shall make no attempt to review all this new material, both in view of its amount and of the fact that most of its originators are contributors to this volume. Rather, I shall focus on some of the results that my colleagues and I have obtained in the last decade.

I am saddened by the fact that Prof. Milton S. Plesset, the gracious host of the Pasadena meeting, is no longer with us. With him we have lost one of the propulsive forces of our community, a scientist whose contributions have shaped bubble research in our time. Personally, I am even more struck as I sorely miss his enlightening mentorship and guiding voice.

2 Spherical Bubble Dynamics

Shortly after the Pasadena meeting Prof. Larry Crum got me involved in his work on bubble levitation [2]. In the attempt to reconcile the data with theory we met some significant differences that, I am sorry to say, have not been resolved to this date. Around the same time I had also started to work on a book on bubble dynamics. Both factors prompted me to look more deeply into the theoretical framework, and especially at the incorporation of liquid compressibility into the well-known Rayleigh-Plesset equation, and at the description of the gas thermo-fluid mechanics. As it turned out, answers to my questions already existed, but were not widely appreciated at the time.

As for liquid compressibility, the problem was not the absence of equations

J. R. Blake et al. (eds.), Bubble Dynamics and Interface Phenomena, 3–16.

A theoretical study of low-frequency oceanic ambient noise

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This paper describes a theoretical model that predicts the wind-dependent ambient noise level in the ocean. Wave breaking and subsequent formation of whitecaps are assumed to be the sole source of sound at the sea surface and their contributions are computed by the use of a simple model for the bubble cloud generated by this process. Inverted hemispherical shapes for which an analytical solution to the wave equation is given are employed to describe the cloud geometry. The input physical parameters to the model are the bubble-size distribution, the dipole strength of the entrained bubbles, the cloud size distribution and growth rate, and the void fraction of the bubble cloud. By using an empirical relation between the whitecap coverage ratio and the wind speed, the underwater ambient noise and surface source levels are computed as a function of frequency and wind speed. Calculated noise levels are in good agreement with the field measurements.

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INTRODUCTION

The correlation between underwater ambient noise level and the wind speed is well documented in the literature (Knudsen *et al.*, 1948; Wenz, 1962). In the low (50–1500 Hz)-frequency range, wind turbulence, ocean spray impact, bubble plume oscillations, and bubble cavitation are cited as possible wind-dependent sources in the literature (Kewley *et al.*, 1990). The cavitation noise has been dismissed as a potential contributor by Prosperetti and Lu (1988) because it requires unrealistically large pressure fluctuations in the ocean. Single bubble oscillations that contribute a great deal to the noise levels at higher frequencies become less of a factor in this range because it is unlikely to find a great many number of bubbles with a natural frequency in the order of few hundred Hz in the ocean. However, the collective oscillations of bubbles suggested independently by Carey and Bradley (1985) and Prosperetti (1985) appear to be a potential source of noise. Experimental studies that have become quite sophisticated in the past few years all point to the fact that wind noise is bubble related.

Earlier measurements of the ambient noise levels are found to be well correlated with the wind speed rather than the wave height (Penhallow and Dietz, 1964) and show a logarithmic dependence with a correlation coefficient that is a function of frequency (Piggott, 1964; Crouch and Burt, 1972). Wilson (1980) pointed out that the noise level follows the whitecap index with increasing wind speed at a fixed frequency and attributed this behavior to spray impact noise (Franz, 1959). Although simultaneous ambient noise and wind speed measurements provide valuable data, they could be contaminated by noise not related to wind, especially at low frequencies where propagation loss is small and bottom reflection high.

In the past decade, an innovative approach has been taken to eliminate contributions from distant sources by using a vertical array of hydrophones instead of just one omnidirectional hydrophone. With this technique, the surface source level just above the array can be measured (Wales and Diachok, 1981; Burgess and Kewley, 1983; Carey *et al.*, 1990; Kennedy and Goodnov, 1990; Kennedy, 1992; Chapman and Cornish, 1993). Another novel idea is to visually record the sea surface and the acoustic signal simultaneously on a video tape so that a direct relation between the noise and the breaking waves can be established (Hollett, 1994).

The collective results of the more recent measurements, as well as the old ones, make it more clear that wave breaking, leading to whitecap formation and bubble entrainment, can be a major contributor as a sea surface source in the frequency range from 50 to 1500 Hz. The modeling of the sound generated by breaking waves has been recently carried out by Loewen and Melville (1991) who considered only emissions from single bubbles. However, it is well known that the acoustic radiation from newly formed bubbles can be affected by the passive scattering of previously entrained bubbles (Updegraff and Anderson, 1991). Therefore their theory is limited to low wind speeds when whitecaps do not exist in significant numbers.

Recently, a great deal of attention has been paid to the understanding and measurement of whitecaps and their importance for noise generation. Detailed and careful experiments have been carried out in the ocean to precisely assess the role of wave breaking. Farmer and Vagle (1989) reported that under identical wind conditions individual wave breaking events produce similar spectral noise levels suggesting a possible universality of this phenomenon. A very detailed description has been given by Monahan and Lu (1990) who identified three types of whitecaps labeled as α or A, β or B, and γ. The type A whitecap represents the initial stage or the birth of a whitecap resulting from a breaking wave. It turns into type B at the end of its life which lasts about 1–2 s. Type A is associated with the air entrainment process and produces a bubble cloud that can penetrate up to one meter below the ocean surface. Most of

LINEAR WAVES IN BUBBLY LIQUIDS

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Abstract. A summary of the current status of the modeling of the propagation of pressure waves in bubbly liquid is presented. An apparent failure of the theory near and above the resonance frequency of the bubbles is found by comparison with experimental data. In the second part of the paper applications to oceanic noise, laboratory bubble clouds, and resonance-parametric generation of low frequency underwater sound are described.

Key words: Bubbly liquids, Two-phase flow, Oceanic noise

1 Foldy's theory

The lowest-order theory of wave propagation in bubbly liquid was essentially worked out by Foldy in a well-known 1945 paper [3], and later applied by him and Carstensen to the analysis of data [4]. The following, although by no means rigorous, is a very simple derivation of Foldy's result.

In the context of potential flow theory, to leading order, bubbles behave as monopoles with strength given by $\dot{v}$, the time derivative of their volume. Consider then N bubbles immersed in an "incident" flow given by a potential ϕ_∞. The total flow due to the incident flow plus the effect of the bubbles has then the potential

$$\phi = \phi_\infty + \sum_{j=1}^{N} \frac{\dot{v}_j}{4\pi|\mathrm{x} - \mathrm{x}_j|}, \tag{1}$$

where x_j is the position of the j-th bubble. If N is large, the preceding relation may be approximated as

$$\phi \simeq \phi_\infty + \int \frac{\dot{v}}{4\pi|\mathrm{x} - \mathrm{x}'|} n(\mathrm{x}')\, d^3x', \tag{2}$$

where n is the bubble number density. Upon taking the Laplacian of this expression, since ϕ_∞ is regular in the region of interest, we have

$$\nabla^2\phi = n\dot{v}, \tag{3}$$

which is essentially Foldy's result for an incompressible liquid. This can be written in a somewhat different form by noting that, for the linear problem,

$$\mathrm{u} = \nabla\phi \qquad P = -\rho\frac{\partial\phi}{\partial t}, \tag{4}$$

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